SIMULTANEOUS POWER GENERATION AND WASTEWATER TREATMENT BY USING AIR-CATHODE SINGLE CHAMBER MICROBIAL FUEL CELL

LIM JIA HAN

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UNIVERSITI MALAYSIA PAHANG

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ABSTRACT

Since the last decade, sustainable energy production and wastewater treatment are of top priority topics in the developing country such as Malaysia. Malaysia is a country that depends on natural gases and fossil fuels as energy sources which are all non-renewable energy sources. Besides, Palm oil mill effluent (POME) is a major wastewater generated in Malaysia during the production of palm oil products. It is highly polluting due to the high content of chemical oxygen demand (COD). Therefore, in order to produce energy and perform wastewater treatment simultaneously, biological wastewater treatment that used microbial fuel cell (MFC) is a promising technology. In this study, simultaneous power generation and wastewater treatment by using air-cathode single chamber MFC was carried out. A non-precious catalyst α-MnO_2 was synthesized to be used for the oxygen reduction reaction (ORR) at the air cathode of the MFC in order to replace the commonly used precious catalyst, platinum (Pt.). The α-MnO_2 was synthesised from $KMnO_4$ in H_2SO_4 solution. It was characterized through X-ray diffraction (XRD), field emission scanning electron microscopy (FESEM), energy dispersive spectroscopy (EDS), and cyclic voltammetry (CV) analysis in order to examine its crystal structure, morphology, chemical composition and also its electrochemical activity in ORR. The XRD results confirmed the formation of α-MnO_2 phase. The ORR activity from CV analysis indicated that the catalyst could be suitable for air cathode MFC. The air cathode single chamber MFC was set up with a 25mL anodic working volume in order to treat POME. Polyvinylpyrrolidone (PVP) was used as the binder for the catalyst to replace the commonly used Nafion solution. Besides, Polyacrylonitrile carbon felt (PACF) was used as electrode for the MFC system. Different catalyst loadings ranging from 0.10 to 0.20g were coated on the projected area of air cathode which is 7.07cm^2 in order to study the effect of catalyst loading on the performance of the MFC based on the power generation and COD removal efficiency from POME. The result obtained showed that the power generation increased with the increase in catalyst loading. The results indicate that the ORR is still the limiting factor for the overall performance of the air cathode MFC. The maximum power density generated was 671.98mW/m^3 and the highest COD removal efficiency was 21.7% when the catalyst loading was 0.20g on the projected area of air cathode. The α-MnO_2 prepared from this study shows great potential to replace the conventional Pt catalyst in cathode.

ABSTRAK

Sejak dekad yang lalu, pengeluaran tenaga mampan dan rawatan air sisa menjadi topik keutamaan di negara-negara yang sedang membangun termasuk Malaysia. Malasyia merupakan negara yang bergantung kepada gas asli dan bahan api fosil sebagai sumber tenaga yang tidak boleh diperbaharui. Selain itu, efluen kilang minyak sawit (EKMS) merupakan sejenis air sisa yang utama dijana di Malaysia semasa process menghasilkan produk-produk minyak sawit. Ia memberi kesan pencemaran yang tinggi disebab oleh kandungan keperluan oksigen kimia yang tinggi di dalamnya. Oleh itu, untuk menghasil tenaga dan menjalan rawatan air sisa dengan serentak, rawatan air sisa biologi yang menggunakan sel bahan api mikrob adalah sejenis teknologi yang memberangsangkan. Dalam kajian ini, hasilan tenaga dan rawatan air sisa dijalankan serentak dengan memggunakan sel bahan api mikrob yang berjenis katod udara kamar. Sejenis pemangkin yang tidak mahal iaitu α-MnO_2 telah disintesikan untuk digunakan dalam reaksi pengurangan oksigen di kamar sel bahan api mikrob bagi menggantikan pemangkin mahal yang biasa digunakan, platinum (Pt.). α-MnO_2 disintesikan daripada reaksi haba oleh $KMnO_4$ didalam larutan H_2SO_4. Ia dicirikan melalui *X-ray diffraction* (XRD), *field emission scanning electron microscopy* (FESEM), *energy dispersive spectroscopy* (EDS), dan analisis *cyclic voltammetry* (CV) untuk meguji struktur kristal, morfologi, komposisi kimia, dan sifat electrokimianya pada aktiviti reaksi pengurangan oksigen. Keputusan XRD yang didapati menentu formasi daripada fasa α-MnO_2. Selain itu, activity reaksi penurunan oksigen daripada analisis CV menunjukkan pemangkin yand disinstesi adalah sesuai untuk kamar sel bahan api mikrob. Sel bahan api mikrob yang berjenis kamar ditubuhkan dengan kebuk anodic yang berisi padu 25mL untuk merawatkan EKMS dan menghasilkan tenaga dengan serentak yang dimangkin oleh α-MnO_2. *Polyvinylpyrrolidone* (PVP) telah digunakan sebagai penjilid untuk pemangkin bagi mengganti penjilid yang biasa digunakan iaitu larutan Nafion. Selain itu, *Polyacrylonitrile carbon felt* (PACF) telah digunakan sebagai elektrod bagi system sel bahan api mikrob. Muatan pemangkin yang berbeza dari 0.10 hingga 0.20g telah bersalut pada pemukaan katod udara iaitu 7.07sm^2 untuk mengaji kesannya kepada prestasi sel bahan api mikrob bagi menghasil tenaga dan kecekapannya untuk menurunkan kandung keperluan oksigen kimia daripada EKMS. Ketumpatan tenaga maksima yang dihasil adalah 671.98mV/m^3 dan kecekapan sebanyak 21.7 telah diciptakan untuk menurunkan kandung keperluan oksigen kimia. Ini adalah dilaku oleh sel bahan api mikrob yang mempunyai muatan pemangkin sebanyak 0.20gram. Pemangkin yang disintesiskan iaitu α-MnO_2 telah menunjuk potensi yang besar untuk mengganti pemangkin kovensional iaitu Pt.

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LIST OF ABBREVIATIONS

A	ampere
I	current
V	voltage
P	power
R	resistance
v	volume
A	Area

Greek

Ω	ohm (resistance)

LIST OF ABBREVIATIONS

BOD	Bio-chemical oxygen demand
COD	Chemical oxygen demand
CV	cyclic voltammetry
EDS	Energy dispersive spectroscopy
FESEM	Field emission scanning electron microscopy
FFB	Fresh fruit bunches
GHG	Greenhouse gas
HRT	Hydraulic retention time
MFC	Microbial fuel cell
ORR	Oxygen reduction reaction
PACF	Polyacrylonitrile carbon felt
PEM	Proton exchange membrane
POME	Palm oil mill effluents
PVP	Polyvinylpyrrolidone
SHE	Standard hydrogen electrode
TSS	Total suspended solid
UASB	Up-flow anaerobic sludge blanket
XRD	X-ray diffraction

CHAPTER 1

INTRODUCTION

1.1 Background

Energy is one of the greatest challenges facing humanity. Energy needs in the world continue to increase, driving demand at an unsustainable pace. The primary source of energy being use worldwide is fossil fuel which is a carbon (C) based chemical such as natural gases and petroleum. The usage of these fuels causes climate change due to the atmospheric release of greenhouse gases like Carbon dioxide (CO_2) and an impending global energy crisis is coming soon. According to Mike & Swadesh (2009), even though the creation of nuclear-power offers a carbon-free approach to energy generation, but no good solutions for nuclear waste exist. Therefore, green energy is still a preferable energy source compare to nuclear energy.

Fossil fuel will not run out suddenly but it is a finite resource. Therefore, energy saving technologies must be develop that can stretch fossil fuel reserves while simultaneously the modification of energy-use patterns and infrastructure to become more sustainable must be carry out (Sun et al., 2009). A sustainable energy port-folio should include a variety of carbon-neutral and renewable energy technologies. Existing technologies based on solar, wind, and biomass energy and infinite resources are meeting the future energy demands of human beings. However, more research and development (R&D) should be carried out in order to improve and optimize these technologies in order to sustain the demands of energy by humankinds.

Apart from energy, the next major concern is wastewater which is the major contributor to the water pollution. According to Shi (2002), until the middle of 18^{th} century, water pollution was essentially limited to small, localized areas. When the Revolution of industrial occurs after the middle of 18^{th} century, the development of the internal combustion engine, and the petroleum-fuelled explosion of the chemical industry happened. With the rapid development rate of various industries, a huge amount of fresh water is used as a raw material, as a means of production which is the process water and for the cooling purposes. Many kinds of raw material, intermediate products and wastes are brought into the water when water passes through the industrial process. So in fact, the wastewater is an “essential by-product” of modern industry, and it plays a major role as a pollution sources in the pollution of water environment (Shi, 2002).

In the case of water pollution, it is primarily caused by the discharge of inadequately treated industrial and municipal wastewater. On the initial discharge, these wastewaters can contain high levels of inorganic pollutants which can be easily biodegradable, but whose impact load on the ecosystems, either in Total Suspended Solids (TSS), Bio-chemical Oxygen Demand (BOD), or Chemical Oxygen Demand (COD) (Czysz & Schneider, 1989). Therefore, in order to overcome this serious problem faced worldwide, increasingly strict regulation on pollution discharge is being implemented by various governmental bodies, which focus primarily on waste reduction (Chan et al., 2009).

Industrial wastewater is one of the important pollution sources in water pollution as mentioned before. According to Shi (2009), during the last century, a huge amount of industrial wastewater was discharged into rivers, lakes and coastal areas. This resulted in serious pollution problems in the water environment and caused negative effects to the eco-system and human’s life. There are many types of industrial wastewater based on different industries and contaminants. Each sector produces its own particular combination of pollutants. Like the various characteristics of industrial wastewater, the treatment of industrial wastewater must be designed specifically for the particular type of effluent produced (Czysz & Schneider, 1989).

Due to the strict regulation on pollution discharge worldwide, wastewater must be collected and conveyed to a treatment facility and treated to remove pollutants to a level of compliance before a municipal or industrial facility can discharge it (Drinan, 2001). There are various technologies for the treatment of different type of wastewater which includes biological treatment.

Many countries, beyond those considered to be ‘developing’, have waste management systems with significant improvement margins to reach worldwide state-of-the art engineering, health and safety standards. These are still characterized by a heavy dependence on landfilling (both engineered and non-engineered) and diverging, but generally low levels of recycling and composting, as well as a general absence of waste-to-energy schemes and plants (Karagiannidis, 2012). Therefore, producing energy from waste has attracted researches attention recently.

Biological treatment used for wastewater treatment appears to be one of the promising technologies. According to Metcalf & Eddy (2003), with appropriate analysis and environmental control, almost all wastewaters containing biodegradable constituents with a BOD/COD ratio of 0.5 or greater can be treated easily by biological means. In comparison to other methods of wastewater treatment, it also has the advantages of lower treatment costs with no secondary pollution (Sponza & Ulukoy, 2005). Both aerobic and anaerobic treatments are biological treatment technologies and are applicable at the Microbial Fuel Cell (MFC).

1.2 Motivation (current issue and potential solution)

Sustainable energy production and wastewater treatment are a top priority in the developing country (Sun et al., 2009) such as Malaysia. According to Viswanathan (2006), the standard of living of the people of any country is considered to be proportional to the energy consumption by the people of that country. Therefore, in order to provide the energy needed and wastewater treatment simultaneously, biological wastewater treatment is used. This technology has the ability to extract energy from the wastewater which makes simultaneously power generation and wastewater treatment possible. This could be done by MFC which is a promising technology (Rabaey & Verstraete, 2005).

Malaysia is a country that depends on oil, coal and natural gas as sources of energy for the country’s economic progress and the nation’s development. However, all of the sources of energy are non-renewable and has raised the concerns of the government and the public on the scarcity of these resources as well as the impact of them on the environment. Moreover, water pollution is also one of the major concerns by Malaysia’s Government and also its residents. As Malaysia is moving towards Wawasan 2020 with the mission of transforming Malaysia to a well-developed and technological advanced country, the industry area is boosting up year after year. In the process of transformation, it had generated tonnes of industrial wastewater every year which contributed to the water pollution. Malaysia as one of the developing country therefore is working hard looking into other sources of energy to meet the nation's high demand of energy needs and moving towards renewable energy for a more sustainable source while at the same time solve the problem faced by industrial wastewater. Therefore, the technology by using MFC can be applied at Malaysia in order to face the two critical problems which is energy and wastewater treatment.

MFC is a device that can achieve synchronous pollutant removal and electricity generation, in the context of wastewater treatment (Cheng et al., 2009). The development and applications of MFC technology is to transform wastewater treatment from an energy-consuming process to a sustainable, energy-saving or energy producing process (Logan & Regan, 2006). MFCs are not new as the concept of using microorganisms as catalysts in fuel cells was explored since 1970s (Ghent, 2013). The reason that leads the research on MFCs is because of MFCs have operational and functional advantages over the technologies currently used for generating energy from organic matter found in wastewater (Rabaey & Verstraete, 2005).

Air cathode MFC is one of the types of MFCs, which use oxygen (O_2) as electron acceptor at the cathode (Shi, et al., 2011). Recently, Air cathode MFCs attract a lot of attentions as the simple structure, relatively low cost and the redox potential of O_2 is relatively high (Liu & Logan, 2004). However, the kinetic reaction rate of the oxygen reduction is very low and the performance of an air cathode MFC is very inefficient without a catalyst. As a common used catalyst for oxygen reduction reaction (ORR), carbon-supported platinum (Pt/C) is one of the most efficient catalysts. However, due to its high-cost that has hindered the development of large scale air cathode MFCs, developing an effective and low-cost catalyst for ORR has aroused extensive research interest (Shi, et al., 2011).

Previously, many noble metal-free catalysts have been investigated such as metal oxides (Morris et al., 2007). Manganese dioxide (MnO_2) was a representative metal oxide which has been studied as a promising alternative electro catalyst for ORR and has been tested in air cathode MFC (Lu et al., 2011). However, there is no research being done yet for the treatment of POME by using MnO_2. Therefore, this is a very good opportunity to carry out research to study the performance for the treatment of POME by using MnO_2.

1.3 Problem statement

Oil palm (scientific term:Elaeis guineensis) is one of the multipurpose crops in the tropical region, particularly in Malaysia and Indonesia (Yejian et al., 2008). During the production of 1 tonne of crude palm oil, more than 2.5 tonnes of palm oil mill effluents (POME) is being produced (Ahmad et al., 2004). Typically, the average COD and BOD in the POME are about 50000 and 25000 mg/L, respectively (Cheng et al., 2009). POME contains high concentration of oil and grease, organic matter, suspended solids and plant nutrients which may result in causing considerable environmental problems if discharged without effective treatment. Nowadays, palm oil mills face a huge challenge in meeting increasingly stringent environmental standards.

In Malaysia, the palm oil industry has grown rapidly over the years and Malaysia has become one of the world's largest producers and exporter of palm oil and its product. In Malaysia, the total production of crude palm oil in year 2008 alone was 17734441 tonnes (Wu et al., 2008). However, the production of this large amount of crude palm oil results in even larger amounts of POME. According to Wu et al. (2010), in year 2008 alone, at least 44 million tonnes of POME was generated in Malaysia and the figures are expected to increase every year. With this significant figure, the palm oil mill industry in Malaysia is identified as one of the largest pollution source in rivers throughout the country. With the rapidly expansion of palm oil industry and public's awareness of environmental pollution, the industry is obliged both socially and aesthetically to treat its effluent before discharging it.

Over the past decades, several economically viable technological solutions have been utilized for the treatment of POME, including simple skimming devices, land disposal, chemical coagulation and flotation, ponding system, ultrafiltration, aerobic and anaerobic biological processes and other specialized treatments (Borja & Banks, 1996). However, most of the treatment method required long retention times and high operating cost such as ponding system. Therefore, new technologies have been created and innovated in order to find an alternative way to treat POME where MFC is one of them. MFC is a technology that applied the concept of aerobic and anaerobic treatment in the context for POME treatment.

As the demands of renewable energy and wastewater treatment become the hot topic worldwide, bioelectricity is another alternative energy carrier that could be obtained from wastewater (Angenent et al., 2004). The MFC is a device that has the ability to converts chemical energy stored in the chemical bonds in organic matter such as wastewater to electrical energy by using microorganisms as a catalyst under anaerobic conditions (Back, et al., 2004).

Apart from MFC, the catalyst at the air cathode compartment which will catalyse the ORR is a major issue. From many of the past researches done, Pt is the first choice of catalyst to be used for the ORR occurred at the air cathode compartment of the MFC. However, Pt is a precious metal and is not an ideal catalyst to be used economically. Therefore, there are many development of Pt-free catalysts being used such as transition metal chalcogenides, nitrogen containing complexes (macrocyclic complexes) (Zhang et al. 2006), non-noble metal electrodes and organometallic complexes (Wang, 2005). From all the Pt-free catalysts, MnO_2 is one of the catalysts which are a promising electro catalyst for ORR. However, the effectiveness of MnO_2 might be lower compared to Pt.

Traditionally air cathodes were made by brushing a catalyst (typically Pt) with a binder, usually Nafion, onto carbon cloth/mesh on the water-facing side of the electrode, and brushing several layers of polytetrafluoroethylene (PTFE) as diffusion layers on the air-side of the cathodes to introduce oxygen transfer and limit water losses (Cheng et al., 2006). However, the noble metal catalyst and the Nafion binder are too expensive to be utilized in large scale. In addition, the brushing method is coarse and labour-consuming for commercialization.

1.4 Objective

This work aims to study the performance of MnO_2 nanoparticle coated air cathode in MFC for simultaneous power generation and COD removal of POME.

1.5 Scope of research

In order to meet the outlined objective, the following scopes of research have been identified.

i. Synthesis and characterization of the catalyst which is MnO_2
ii. Cold Pressing of MnO_2 with the Nafion Membrane to form the air cathode
iii. Characterization of POME which is the percentage of COD using COD reactor
iv. Carry out a set of experiments with different composition of MnO_2 on the air cathode
v. Measurement of the percentage of COD removed and power generated
vi. Justify the efficiency

1.6 Structure of thesis

The structure of the reminder of the thesis is outlined as follow:

Chapter 2 presents the studies of the POME and also the treatment of POME using different technology. Besides than that, the types of MFC and their function will be included with argument of the advantages and disadvantages for both single and double chamber MFC. Detailed study about the air cathode will be included as well. Moreover, the catalyst used for the study which is MnO_2 to replace the precious metal catalyst Pt will be discuss by giving supportive statements for choosing it. Previous work done on the treatment of wastewater using MFC will also be discussed and also the catalyst used.

Chapter 3 describes the chemicals, materials, synthesis and characterization of catalyst, characterization of POME, and also the experimental procedure. Eleven sections in this chapter are introduction, chemicals, the synthesis and characterization of MnO_2 catalysts, characterization of POME, PEM preparation, electrodes preparation, Inoculation, MFC construction, analysis and calculation, evaluation of MFC performance, and also operating condition optimization.

Chapter 4 is devoted to a discussion of the laboratory work done on the catalyst characterization results and the MFC performance based on different catalyst loadings. The data obtained will be discussed and comparison will be made with previous work based on similarities and differences.

Chapter 5 will present the conclusion and recommendation. The objectives and purpose of this research study will be concluded and some recommendations or suggestions will be suggested so that this research data could contribute to other research in the future.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter overview

This chapter presents the studies of the POME and also the treatment of POME using different technology. Besides than that, the types of MFC and their function will be included with argument of the advantages and disadvantages for both single and double chamber MFC. Detailed study about the air cathode will be included as well. Moreover, the catalyst used for the study which is MnO_2 to replace the precious metal catalyst Pt will be discuss by giving supportive statements for choosing it. Previous work done on the treatment of wastewater using MFC will also be discussed and also the catalyst used.

2.2 Introduction

Palm oil industry is one of the leading agricultural industries in Malaysia with average crude palm oil production of more than 13 million tonne per year. During the production of the crude palm oil, POME is generated at the same time. POME is a highly polluting wastewater with high COD and BOD. According to Abdurahman et al (2013), POME is an important source of inland water pollution when released into local rivers or lakes without treatment. Over the past 20 years, the technique available for the treatment of POME in Malaysia has been biological treatment, consisting of anaerobic, facultative and aerobic pond systems (Ma, 1999). From all these technology, anaerobic treatment can be implemented in MFC for the treatment of POME while simultaneously generates power. However, previous studies of MFC used precious metal catalyst (Pt.) for the ORR occurred at the cathode side. Therefore, it is necessary to develop a non-precious metal catalyst for the replacement of Pt. MnO_2 is one of the promising non precious catalysts for the ORR and is a potential candidate to develop an economical MFC for simultaneous power generation and wastewater (POME) treatment.

In this chapter, the previous researches related to this topic will be studied and reviewed especially researches that discussed about the types of MFC and also the treatment of POME using anaerobic treatment. The catalyst used for previously studies will also be study especially Pt and MnO_2.

2.3 POME

2.3.1 General properties of POME

POME is one of the industrial wastewater generated from the production of crude palm oil. The general properties of POME are listed in Table 2-1 while Table 2-2 lists the contents in POME

Table 2-1: General properties of POME (Kamal et al., 2012).

Physical & Chemical Properties	Unit	Value
Moisture Content	%	93.4
Ash	%	1.06
Total Solid	g	65 - 80
Soluble Fibre	%	SS 1.12
Non Soluble Fibre	%	TS 3.9
COD	mg/L	15000-100000
BOD	mg/L	25000

Table 2-2: Contents of POME (Kamal et al., 2012).

Parameter	Average	Metal	Average
pH	4.7	Phosphorous (P)	180
Oil and Grease	4000	Potassium (K)	2270
TSS	18000	Magnesium (Mg)	615
Total Volatile Solids	34000	Calcium (Ca)	439
Amonical Nitrogen	35	Baron (Ba)	7.6
Total Nitrogen (N)	750	Iron (Fe)	46.5
		Manganese (Mn)	2
		Copper (Cu)	0.89
		Zinc (Zn)	2.3

All in mg/l except pH.

POME is a type of industrial wastewater. It is a viscous brown liquid. In the general appearance, POME is a yellowish acidic wastewater. It is being generated from the production of palm oil, which is one of the most prevalent high-yield crop products of tropical countries like Malaysia (Ma & Ong, 1985). During the production of 1 tonne of crude palm oil, about 2.5 tonnes of POME will be produced. According to Chungsiriporn et al., 2006), about 1.5 m^3 water are used for process one tonne of fresh fruit bunches (FFB) to become crude palm oil and half of this quantity results in POME which is $0.75m^3$. For every 1 m^3 of POME released, when treating using the conventional biological treatment system, about 14.15 m^3 of methane (CH_4) gas is released (Noraziah, 2011).

POME, when fresh, is a thick brownish colloidal mixture of water, oil and fine suspended solids. It is hot (80 – 90 ^oC) and possesses a very high contents of BOD and COD, which is 100 times as polluting as domestic sewage (Ma et al., 1993). Since POME contains high concentration of BOD, COD, oil and grease, organic matter, and also TSS, it can cause significant environmental problems if discharged without effective treatment. Due to the high demand of crude palm oil in the world today, the palm oil mills face a huge challenge in meeting increasingly stringent environmental standards (Cheng et al., 2009).

2.3.2 Advantages and disadvantages of POME

As the properties of POME listed in Table 2-1, POME will be the source of pollutants when it is discharged into waterways which can contaminate the water source that is vital as drinking water for human beings and also the animals. In addition, it is also particularly harmful to aquatic ecology by creating highly acidic environments or causing eutrophication (where excessive algal growth occurs on the surface of the water) (ZSL, 2013).

Apart from water pollution, POME is also one of the sources of greenhouse gas (GHG) emissions. The most famous treatment of POME is ponding system. Therefore, during the treatment of POME, it is typically released into open-air holding ponds for remediation, thereby releasing carbon dioxide (CO_2), CH_4, hydrogen sulphide (H_2S) which contribute to the greenhouse effect and causes global climatic change (ZSL, 2013).

Even though POME contributed a lot to the negative effects to the environment, it also contains some nutrient elements for positive purposes. The N, P, Mg and Ca are the vital nutrient elements for plant growth (Habib et al., 1997). Due to the non-toxic nature and fertilizing properties, POME can be used as fertilizer or animal feed substitute, in terms of providing sufficient mineral requirements (Rupani et al., 2010).

Last but not least, according to a study conducted by Wu et al. (2009), there were also a lot of biotechnological advances in the sustainable reuse of POME which include of POME as fermentation media, antibiotics, bio insecticides, solvents (acetone-butanol-ethanol: ABE), organic acid and also enzymes.

2.4 POME treatment

Over the past decades, several economically viable technological solutions have been utilized for the treatment of POME in order to control POME pollution, including simple skimming devices, land disposal, chemical coagulation and flotation, ultra filtration, aerobic and anaerobic biological processes and other specialized treatments (Ahmad et al., 2005). However, few have been put into full-scale application because of their unsatisfactory performance and/or high operating costs. Compared with the physical and chemical technologies, conventional biological treatment methods of anaerobic, facultative, and aerobic degradation are more widely used in the treatment of POME (Yejian et al., 2008).

2.4.1 Anaerobic treatment

Of all of the technologies used in POME treatment, anaerobic treatments are most widely used because of their particular advantages, such as energy efficiency, low biomass yield, low nutrient requirement, and high volumetric organic loading (Yejian et al., 2008). High rate anaerobic reactors such as the up-flow anaerobic sludge blanket (UASB) presently play an important role in POME treatment. The distinct characteristic of these reactors is the existence of granular sludge, which can enhance treatment efficiency. For example, Borja et al., (1995) obtained satisfactory results using UASB reactors to treat POME. Furthermore, during the anaerobic treatment of POME, CH_4 and hydrogen (H_2) gas are generated which can reduce the demand on energy resources (Cheng et al., 2010).

Even though anaerobic reactors are a good way to treat POME, however, the application of anaerobic biological processes is presently limited by their relatively low efficiency regarding biogas collection, purification and utilization. In addition, due to the higher cost, most of the palm oil mills have not equipped the CH_4 recovery and utilization system yet. Usually, the biogas is directly discharged to the atmosphere, thus exacerbating the greenhouse effect (Cheng et al., 2010).

Beside than UASB, anaerobic ponding system is another anaerobic treatment for POME that was used widely. According to Yejian et al. (2008), there is about 85% of POME treatment is based on the facultative anaerobic pond system. This technology is relatively cheap and very stable in used. Besides, the energy required is minimal while the maintenance and operating costs are relatively low (Chin et al., 1996).

However, ponding system required long retention times and large treatment areas because the system usually consists of a de-oiling tank, acidification, anaerobic and facultative ponds with hydraulic retention times (HRT) of 1,4,45 and 16 days (Ma et al., 1993). Moreover, the treated POME using ponding system sometimes couldn't meet the discharge standard (Chin et al., 1996) and the removal of nitrogen from POME is usually unsatisfactory because of nitrification is an uncommon phenomenon in the ponding system (John, 1985). Table 2-3 shows various types of anaerobic treatment for POME and their performances.

Table 2-3: Performance of anaerobic treatment on POME.

Treatment processes	**COD Influent(mg/L)**	**Overall Reduction of COD (%)**	**References**
Anaerobic suspended growth processes	67,000	95.6	Chin & Wong, 1983
Semi-continuous digester	70,000	75	Cail & Barford, 1985
Digestion tank	54,510	93.6	Edewor, 1986
Completely mixed reactors	48,200	83.4	Borja et al., 1995
Immobilized cell bioreactor	69,000	96.2	Borja & Banks, 1994
Ponding System	42,500	96	Borja & Banks, 1996

2.4.2 Aerobic treatment

Apart from anaerobic treatment, another common treating method for POME is aerobic treatment. In general, the system using an aerobic digestion for POME treatment would be more efficient and the HRT even shorter than for anaerobic digestion (Agamuthu, 1995). For instance, Karim & Kamil (1989) found that by using the fungal inoculum, a reduction in COD of the POME of more than 95% could be achieved after 10-14 days of fermentation. Besides, Oswal et al. (2002) also found that POME treatment by using *Yarrowia lipolytica* NCIM 3589, which is known to degrade alkanes in crude oil, provided a COD reduction of about 95% with a short retention times of only 2 days.

Even though the aerobic treatments do have some advantages, however, it also consists of some disadvantages. Aerobic treatment method required high energy input for aeration (Jr et al., 1999). Besides, the rate of pathogen inactivation is lower in aerobic sludge compared to anaerobic sludge, thus it is unsuitable for land applications (Doble & Kumar, 2006). Table 2-4 shows various types of aerobic treatment for POME and their performances.

Table 2-4: Performance of aerobic treatment on POME.

Treatment processes	**COD Influent(mg/L)**	**Overall Reduction of COD (%)**	**References**
Pressurized activated sludge process	9,210	97.7	Ho & Tan, 1988
Aerobic treatment with *Yarrowia lipolytica*	243,000	96.9	Oswal et al., 2002
Aerobic treatment with *Y.* lipolytica + 0.03 g/L $FeCl_3$	246,000	99.4	Oswal et al., 2002
Activated sludge reactor	3,908	98	Vijayaraghavan et at., 2007

As from the POME treatment methods such as anaerobic method and aerobic method, it could be found that both have its advantages and disadvantages, therefore, the aerobic and anaerobic treatment methods should be combine in order to treat POME in a more efficiency way. This concept can be implant at the MFC device which consists of two main compartments the anode for anaerobic treatment and the cathode for the aerobic treatment (Cheng et al., 2010). Table 2-5 summarize the various treatment process of POME.